

Jet Engine Performance Enhancement Through Use of a Wave-Rotor Topping Cycle

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Summary

A simple model is used to calculate the thermal efficiency and specific power of simple jet engines and jet engines with a wave-rotor topping cycle. The performance of the wave rotor is based on measurements from a previous experiment. Applied to the case of an aircraft flying at Mach 0.8, the calculations show that an engine with a wave-rotor topping cycle may have gains in thermal efficiency of approximately 1 to 2 percent and gains in specific power of approximately 10 to 16 percent over a simple jet engine with the same overall compression ratio. Even greater gains are possible if the wave rotor's performance can be improved.

Introduction

The wave rotor is a device that uses aerodynamic waves to compress and expand gas instead of the mechanical compressors and turbines of conventional turbomachinery. It is not new, having been invented by Seippel in 1940 (ref. 1). Although its major application has been as an automobile supercharger (refs. 2 to 6), it was originally intended as a gas-turbine topping cycle (ref. 1). The advantage of a wave rotor as a topping cycle is that it allows combustion temperatures that are higher than the turbine inlet temperature because the gas entering the turbine has already been cooled by the expansion wave in the wave rotor. This was a desirable feature for early jet engines, which suffered from a lack of suitable turbine materials. However, the materials problem was solved before the wave rotor was adequately developed for this purpose, and the use of the wave rotor as a gas-turbine topping cycle appears to have been shelved.

Currently, turbine inlet temperature is again a limitation on jet-engine performance, and turbine inlet temperatures have been almost constant over the last 10 years (ref. 7). Materials development is aimed at ceramic blades, which are brittle, expensive, and difficult to machine. As a result, there is renewed interest in wave rotors (refs. 8 and 9). Despite the previous interest, little appears to have been done to indicate generally the extent of the performance improvement that can be achieved. Consequently, in this report, simple models will be used to estimate this enhancement.

Symbols

C_{p1}	specific heat of air in compression stages of engine
C_{p2}	specific heat of gas in expansion stages of engine

OPR	overall engine compression ratio, $p_{3.2}/p_0$
p_a	free-stream static pressure
p_i	total pressure at station i
M	flight Mach number
m_f	fuel-air ratio
PD	combustor pressure ratio for simple jet; ducting pressure ratio for engine with wave-rotor topping cycle
PM	ratio of free-stream total to static pressure, $(1 + 0.2M^2)^{3.5}$
PO	ratio of pressure of gas leaving wave rotor to pressure of air entering wave rotor, $p_{4.1}/p_{3.1}$
PR	compression ratio of wave rotor, $p_{3.2}/p_{3.1}$
Q	caloric value of fuel
R	compression ratio of jet engine compressor (i.e., shaft compression ratio, p_3/p_0)
T_a	free-stream static temperature, $T_0/(1 + 0.2M^2)$
T_i	total temperature at station i
V	flight velocity
W	specific work of engine/wave-rotor combination
W_C	specific work of engine compressor
W_E	specific work of complete expansion after wave rotor
W_{ER}	specific work of wave-rotor expansion
W_R	specific work of wave-rotor compression
W_T	specific work of engine turbine
γ_1	specific heat ratio of air
γ_2	specific heat ratio of combustion gases
η	efficiency of engine/wave-rotor combination
η_B	combustor efficiency
η_C	compressor polytropic efficiency
η_E	expansion efficiency of wave rotor
η_M	mechanical efficiency
η_R	compression efficiency of wave rotor
η_T	turbine polytropic efficiency

Subscripts

0, 3, 3.1, 3.2, 4.1, 4.2, 5, stations indicated in figure 1(a)

Model Description

Wave rotors can operate on a variety of cycles, depending on the intended application. For example, a three-port cycle has been used by Kentfield both as a flow divider and equalizer (ref. 10). A flow divider takes in a single stream of gas at the input port and delivers it to two output ports: one at higher stagnation pressure than the input, the other at lower stagnation pressure. An equalizer does the reverse (i.e., it takes in two streams at different pressures and delivers a single stream at one pressure). Neither of these cycles employs a combustion stage. In order to use a wave rotor as a topping cycle, assuming that combustion is performed outside the rotor, at least four ports are required: input, output to the combustion chamber, return from the combustion chamber, and final output. Taussig (ref. 8) considered a five-port cycle and a variation, a nine-port cycle. The five-port cycle has two output streams, each at different stagnation pressures, and thus requires an extra turbine to extract the energy from the high-pressure stream. The cycle used by Brown Boveri (ref. 4) creates high stagnation pressure in the output to the combustor, from which work must be extracted before returning the gas to the wave rotor. In contrast, the cycle proposed by General Electric, as reported by Mathur (ref. 11), is a four-port cycle with the single final output stream at higher pressure than the input stream. Such a cycle is eminently suitable for application as a jet-engine topping cycle, requiring no special turbine. Calculations of the performance of four-port cycles have recently been made by Paxson (ref. 12), using a computational fluid dynamics (CFD) approach, and will be used in this work.

The use of a four-port wave rotor as a topping cycle is illustrated in figure 1(a). Compressed air from a conventional compressor (station 3) is sent to the wave rotor where it is further compressed, leaves the wave rotor (at station 3.2) to enter the combustor, exits from the combustor (at station 4.0) to reenter the wave rotor where it expands (compressing the input gas in the process), and finally exits (station 4.1) to enter the conventional turbine. Because the gas is heated in a conventional, constant-pressure combustor, the cycle is a Brayton cycle, and the whole cycle is as indicated in the enthalpy-entropy diagram of figure 1(b). The basic engine is assumed to be a simple jet engine, so that the turbine work equals the compressor work.

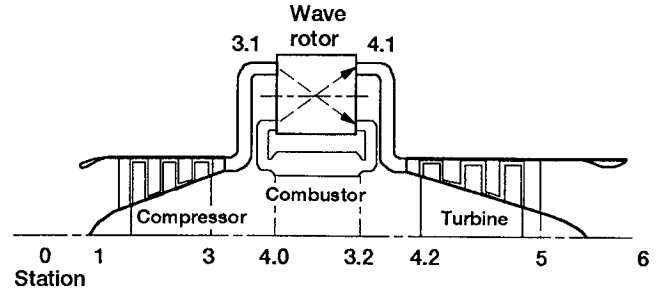
If it is assumed that the compressor has a compression ratio R , called the shaft compression ratio to distinguish it from the overall compression ratio OPR (which includes the wave-rotor compression), and a polytropic efficiency η_C , then

$$W_C = C_{p1}T_0 \left[R^{(\gamma_1-1)/\eta_C \gamma_1} - 1 \right] \quad (1)$$

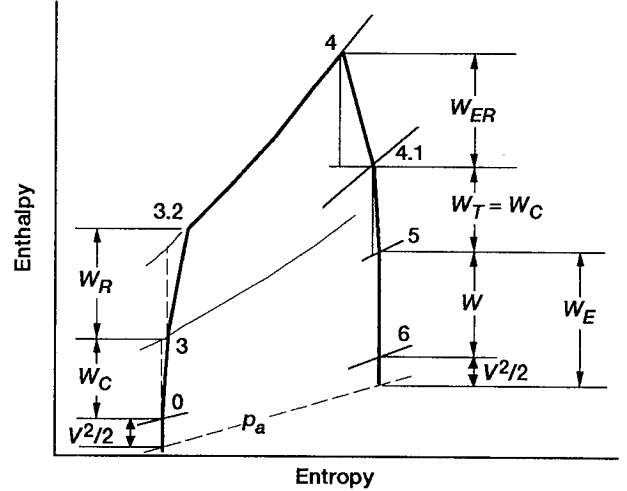
and the temperature after compression is

$$T_3 = T_0 R^{(\gamma_1-1)/\gamma_1 \eta_C} \quad (2)$$

The compressed air passes through the wave-rotor-combustor cycle and emerges at station 4.1. Because fuel has been added in



(a) Schematic diagram showing various stations.



(b) Enthalpy-entropy diagram.

Figure 1.—Schematic and enthalpy-entropy diagrams of jet engine with wave-rotor topping cycle.

the combustor, the mass of gas per pound of input air is $(1 + m_f)$. This gas passes to the turbine, which drives the compressor. The turbine must supply enough work, after losses in the mechanical shaft connecting the two, to drive the compressor. Thus, the temperature drop in the turbine is calculated from

$$(1 + m_f) C_{p2} (T_{4.1} - T_5) = \frac{C_{p1} (T_3 - T_0)}{\eta_M} \quad (3)$$

that is, the temperature of the gas leaving the turbine T_5 is

$$T_5 = T_{4.1} - \frac{C_{p1}}{C_{p2}} \frac{(T_3 - T_0)}{(1 + m_f) \eta_M} \quad (4)$$

and hence the pressure of the gas leaving the turbine is given by

$$\frac{p_5}{p_{4.1}} = \left(\frac{T_5}{T_{4.1}} \right)^{\gamma_2 / (\gamma_2 - 1) \eta_T} \quad (5)$$

where the pressure $p_{4,1}$ is found from

$$p_{4,1} = p_a \times R \times PM \times PO \times PD \quad (6)$$

The gas leaving the turbine can do work W_E in expanding to ambient pressure p_a , given by

$$W_E = (1 + m_f) C_{p2} T_5 \left[1 - \left(\frac{p_a}{p_5} \right)^{(\gamma_2 - 1)/\gamma_2} \right] \quad (7)$$

This is the expansion work available from the cycle, which could be extracted in a turbine to drive a propeller or fan or used to provide exhaust velocity in a jet. Each of these extraction schemes has its own inefficiencies, and so, for greater generality, the expansion work will simply be calculated as if it were extracted in a 100-percent-efficient turbine. However, not all the expansion work W_E is available: After extraction of the work there must be sufficient enthalpy left to produce a velocity in the exhaust equal to the flight velocity, or else there will be a net thrust or drag on the engine. Thus, the available specific work is

$$W = W_E - \frac{V^2}{2} = (1 + m_f) C_{p2} T_5 \left[1 - \left(\frac{p_a}{p_5} \right)^{(\gamma_2 - 1)/\gamma_2} \right] - C_{p1} (T_0 - T_a) \quad (8)$$

The overall thermal efficiency of the cycle is the available work divided by the heat added to produce it, that is,

$$\eta = \frac{W}{m_f Q} \quad (9)$$

In order to evaluate this expression, it is necessary to calculate the fuel-air ratio m_f . By balancing the heat supplied in the combustor,

$$\begin{aligned} \eta_B m_f Q &= C_{p2} T_4 (1 + m_f) - C_{p1} T_{3,2} \\ &= [C_{p2} T_{4,1} (1 + m_f) + W_{ER}] - [C_{p1} T_3 + W_R] \\ &= (1 + m_f) C_{p2} T_{4,1} - C_{p1} T_3 + (W_{ER} - W_R) \end{aligned} \quad (10)$$

But because the compression work in the wave rotor will equal the expansion work,

$$W_{ER} - W_R = 0$$

and hence,

$$m_f Q = \frac{1}{\eta_B} [(1 + m_f) C_{p2} T_{4,1} - C_{p1} T_3] \quad (11)$$

and the thermal efficiency can be written as

$$\eta = \frac{\eta_B W}{(1 + m_f) C_{p2} T_{4,1} - C_{p1} T_3} \quad (12)$$

Thus if, for a given temperature rise across the wave-rotor-combustor system, $T_{4,1} - T_3$, the pressure rise is known, so that $p_{4,1}$ can be calculated, the specific work and efficiency of the engine can also be evaluated. The dependence of the wave-rotor pressure rise on the wave-rotor temperature rise will be called the wave-rotor characteristic. It is a measure of the wave-rotor's efficiency.

Wave-Rotor Characteristic

A general approach to the wave-rotor characteristic can be made by way of thermodynamics, like the approach used earlier for the engine. Thus, if the wave rotor has a compression ratio denoted by PR, the compression work is

$$W_R = C_{p1} (T_{3,2} - T_{3,1}) = \frac{C_{p1} T_{3,1}}{\eta_R} \left[PR^{(\gamma_1 - 1)/\gamma_1} - 1 \right] \quad (13)$$

and the expansion work is

$$W_{ER} = C_{p2} (T_4 - T_{4,1}) = \eta_E C_{p2} T_4 \left[1 - \left(\frac{PO}{PR} \right)^{(\gamma_2 - 1)/\gamma_2} \right] \quad (14)$$

where PO is the pressure ratio $p_{4,1}/p_{3,1}$.

Equating the compression work to the expansion work leads, after some algebra, to

$$PO = PR \left\{ \frac{1 - \frac{C_{p1}}{C_{p2}} \frac{(1 - \eta_E)}{\eta_E \eta_R} \frac{T_{3,1}}{T_{4,1}} \left[PR^{(\gamma_1 - 1)/\gamma_1} - 1 \right]}{1 + \frac{C_{p1}}{C_{p2}} \frac{T_{3,1}}{\eta_R T_{4,1}} \left[PR^{(\gamma_1 - 1)/\gamma_1} - 1 \right]} \right\}^{\gamma_2 / (\gamma_2 - 1)} \quad (15)$$

This relation is the desired wave-rotor characteristic equation giving the pressure rise across the wave rotor as a function of the temperature ratio across the wave rotor. Unfortunately, it includes

the wave-rotor compression ratio PR, which is also a function of the temperature ratio, and the wave-rotor compression and expansion efficiencies, which are not known. In principle, if an analytical model of the wave-rotor cycle could be developed, the wave-rotor compression ratio and efficiencies could be calculated. However, the cycle is sufficiently complicated that it proved impossible to create an analytical model.

Alternative means of determining the wave-rotor characteristic are thus needed. One way is to use the CFD code developed by Paxson (ref. 12), and another is to use experimental data. Mathur (ref. 11) has reported work by General Electric on a four-port rotor. This work included experimental determination of the characteristic; the results are reproduced in figure 2. Also included in figure 2 is a numerical calculation of the characteristic using the CFD code developed by Paxson (ref. 12). There are two possible causes for the discrepancy between the CFD results and the experimental points. One is that the CFD calculation has different timing for each value of temperature ratio, whereas the General Electric data presumably are for a fixed geometry. Another is that friction is included in the code, but the calculation was performed for a relatively large rotor, for which friction should be less important than in the small General Electric rotor. Two additional curves are shown in figure 2. One is a curve generated by using equation (15) with $\eta_R = \eta_E = 0.83$, PR = 1.8, and $\gamma_2 = 1.3$. It is sufficiently close to both the General Electric results and the CFD code results that it can be used as the rotor characteristic for the purpose of this report. This is not meant to imply that PR = 1.8 or that the efficiencies are constant. Indeed as the temperature ratios

increase, so will PR, but at the same time the efficiencies will drop. However, unless the ratio PR and the efficiencies are obtained from the CFD program, there is no basis for determining their values more exactly. It is simpler to use constant values that generate a curve which should approximately equal an actual curve. In fact there will not be any single actual curve because the real curve will be a function of the efficiencies, which will vary from rotor to rotor depending on the exact cycle used and the configuration of the hardware. For generic purposes, equation (15) will suffice, and for the balance of this report, the expression "wave-rotor characteristic" will mean equation (15) with PR = 1.8 and $\eta_R = \eta_E = 0.83$ unless otherwise indicated.

In previous wave-rotor work it has not always been possible to evaluate η_R and η_E separately; instead, their product has been determined. Thus, Taussig (ref. 8) reported $\eta_R \eta_E = 0.7$ to 0.74, and Moritz (ref. 13), in experiments at Rolls-Royce, found $\eta_R \eta_E = 0.6$. Kollbrunner (ref. 2) measured η_R alone as 0.65 to 0.68. Approximately then, the GE results correspond to $\eta_R \eta_E = (0.83)^2 = 0.69$. This result is in reasonable agreement with Taussig and Moritz, although rather higher than Kollbrunner. Thus, it appears that use of $\eta_R = \eta_E = 0.83$ is consistent with results from other work on wave rotors.

In addition to cases calculated using this wave-rotor characteristic, additional cases were run using an "advanced" wave rotor. The advanced wave-rotor characteristic was simply obtained by doubling PR (i.e., using PR = 3.6 in eq. (15) again with $\eta_R = \eta_E = 0.83$) and is also plotted in figure 2. Whether such a wave-rotor characteristic is possible is not currently known—certainly it is not with the four-port cycle of the kind explored by General Electric. Brown-Boveri has achieved compression ratios up to 7 according to L. Mathews in a private communication. However, this was with a cycle that generates a large stagnation pressure difference across the combustor, requiring a turbine in this part of the cycle if this pressure difference is to be converted to useful work efficiently. This may well prove to be the only way to exploit large wave-rotor pressure ratios but will require a total engine redesign. Thus, it is not clear whether, or how, the performance indicated by the advanced wave rotor will be obtainable, but it is an interesting speculation.

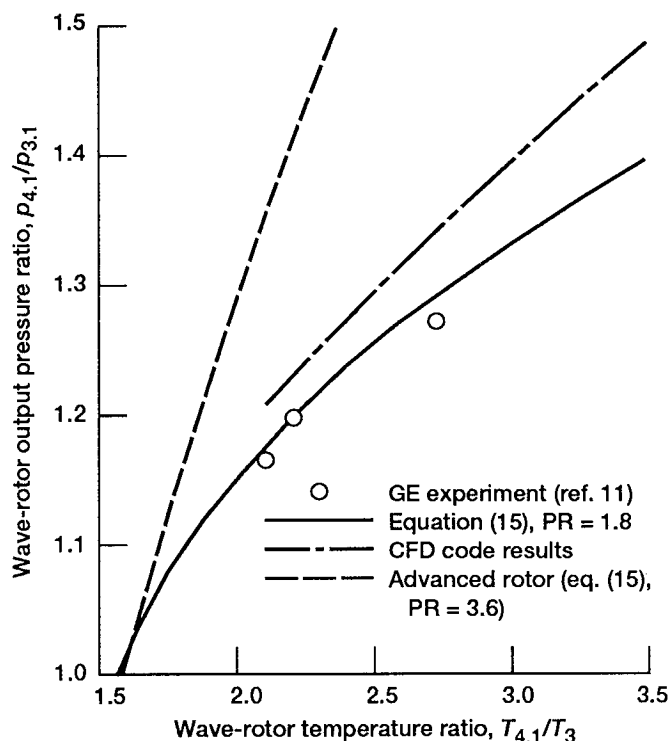


Figure 2.—Pressure ratio across wave rotor as function of temperature ratio across it.

Application to Engine Performance

With an expression for the wave-rotor characteristic given, it is possible to calculate the specific power and efficiency of engines with a wave-rotor topping cycle. A reasonable case to consider is that of an aircraft flying at an altitude of 35 000 ft at Mach 0.8. For this case the stagnation temperature of the incoming air is 444 °R, and the total to static pressure ratio is PM = 1.524.

If a turbine inlet temperature $T_{4,2}$ (assumed equal to $T_{4,1}$) and a shaft compression ratio are chosen, the temperature T_3 is given by equation (2), and hence the wave-rotor temperature ratio $T_{4,2}/T_3$ is known. The ratio PO follows from the wave-rotor characteristic, and thus the specific power and efficiency can be found from equations (8) and (12). By setting PO = 1 the calcu-

lation becomes that for a simple jet engine without a wave rotor. Thermal efficiencies for simple jet engines of varying compression ratio calculated this way are shown in figure 3, together with points calculated by using the ONX program for jet engine performance of Mattingly, Heiser, and Daly (ref. 14) with $\gamma_1 = 1.4$ and $\gamma_2 = 1.3$. Other values used were $\eta_C = 0.9$, $\eta_T = 0.91$, $\eta_B = 0.995$, $PD = 0.95$, and $\eta_M = 0.98$. The agreement between the results of the ONX program and those of the present calculation is excellent, giving confidence in the method.

Figure 4 shows that the wave-rotor temperature ratio is determined more by the value of R than by the choice of turbine inlet temperature for the range of turbine inlet temperatures chosen. For a fixed turbine inlet temperature using a high value of R leads to a low wave-rotor temperature ratio because the value of $T_{3,1}$ increases with R but $T_{4,1}$ is constant. In turn this results in a small pressure rise across the wave rotor, so that little benefit results from its use. The opposite is true for low values of R . The results of calculations to determine the effect of adding a wave-rotor topping cycle to a jet engine for turbine inlet temperatures of 2900, 3100, 3300, and 3500 °R are given in figures 5 and 6 as a function of shaft compression ratio.

At a turbine inlet temperature of 2900 °R the advanced wave-rotor performance was lower than the simple jet engine performance for shaft compression ratios above about 80. In other words, if the jet engine has a shaft compression ratio of 80 or greater, adding an advanced wave rotor would result in lower performance! Reference to the advanced wave-rotor characteristic in figure 2 shows that it has a threshold slightly above a temperature ratio of 1.6. Wave-rotor temperature ratios below 1.6 will generate wave-

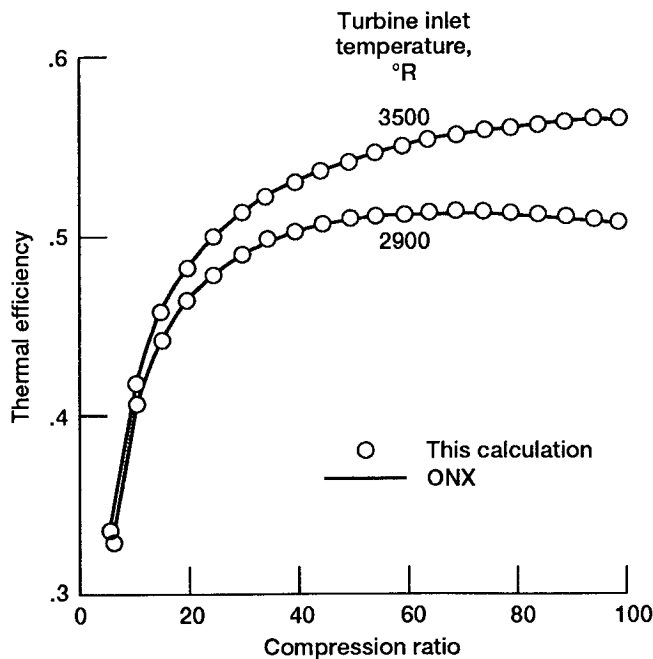


Figure 3.—Thermal efficiency of simple jet engine as function of compression ratio calculated with present model and also with computer code ONX of reference 14 for turbine inlet temperatures of 2900 and 3500 °R.

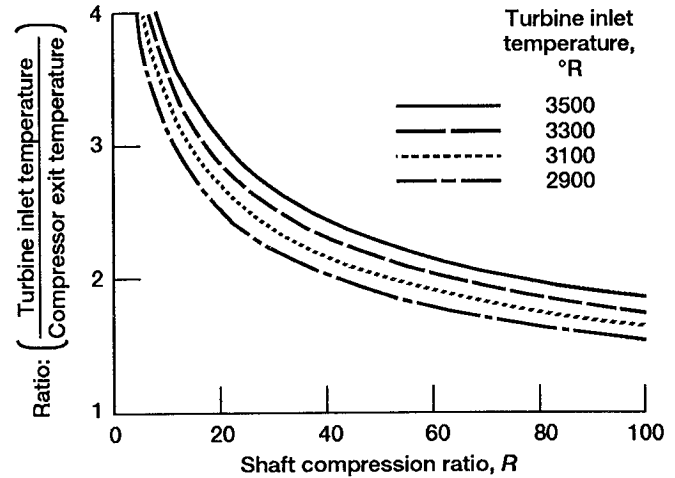


Figure 4.—Ratio of turbine inlet temperature to compressor exit temperature (i.e., temperature ratio across wave rotor) as function of shaft compression ratio.

rotor pressure ratios less than 1. A wave-rotor temperature ratio of 1.6 occurs for $R = 80$ and a turbine inlet temperature of 2900 °R.

At first sight the performance improvements to be gained by adding a wave-rotor topping cycle seem relatively small, and indeed, the efficiency gains are not spectacular. However, the efficiency gains are accompanied by increases in specific power, which is not the case if one were simply to increase the compression ratio. For example, if one takes as a base case a simple jet engine with a compression ratio of 33.3, which is typical of some of today's large engines, and a turbine inlet temperature of 3300 °R, then from figures 5 and 6 the efficiency is 51.3 percent and the specific power is 510 hp/lb-sec. If, in an effort to improve efficiency, one were to increase the conventional compression ratio by 1.8 (i.e., to 60), the efficiency would increase to 54.2 percent but the specific power would drop to 480 hp/lb-sec. Alternatively, if a wave-rotor topping cycle were used to achieve the same overall compression ratio of 60, the efficiency would increase to 54.3 percent, and the specific power would also increase to 537 hp/lb-sec (i.e., 12 percent more than the jet engine with an overall pressure ratio of 60).

In order to see more clearly the comparison between a jet engine and a jet-engine/wave-rotor combination of the same overall compression ratio, the thermal efficiency and specific power are plotted against overall compression ratio (i.e., $PR \times R$) in figures 7 and 8. For the whole range of compression ratios considered, the jet-engine/wave-rotor combination has about the same or slightly higher efficiency and significantly higher specific power than the jet engine alone, particularly at high compression ratios.

These numerical results assumed only the wave-rotor performance demonstrated by General Electric and not the advanced wave-rotor performance. Obviously, if better wave-rotor performance were available, the jet-engine/wave-rotor combination would be even more promising. Of course, the increase in specific power with a wave rotor is not obtained without a price—the price being an increase in combustion temperature. This is shown in figure 9,

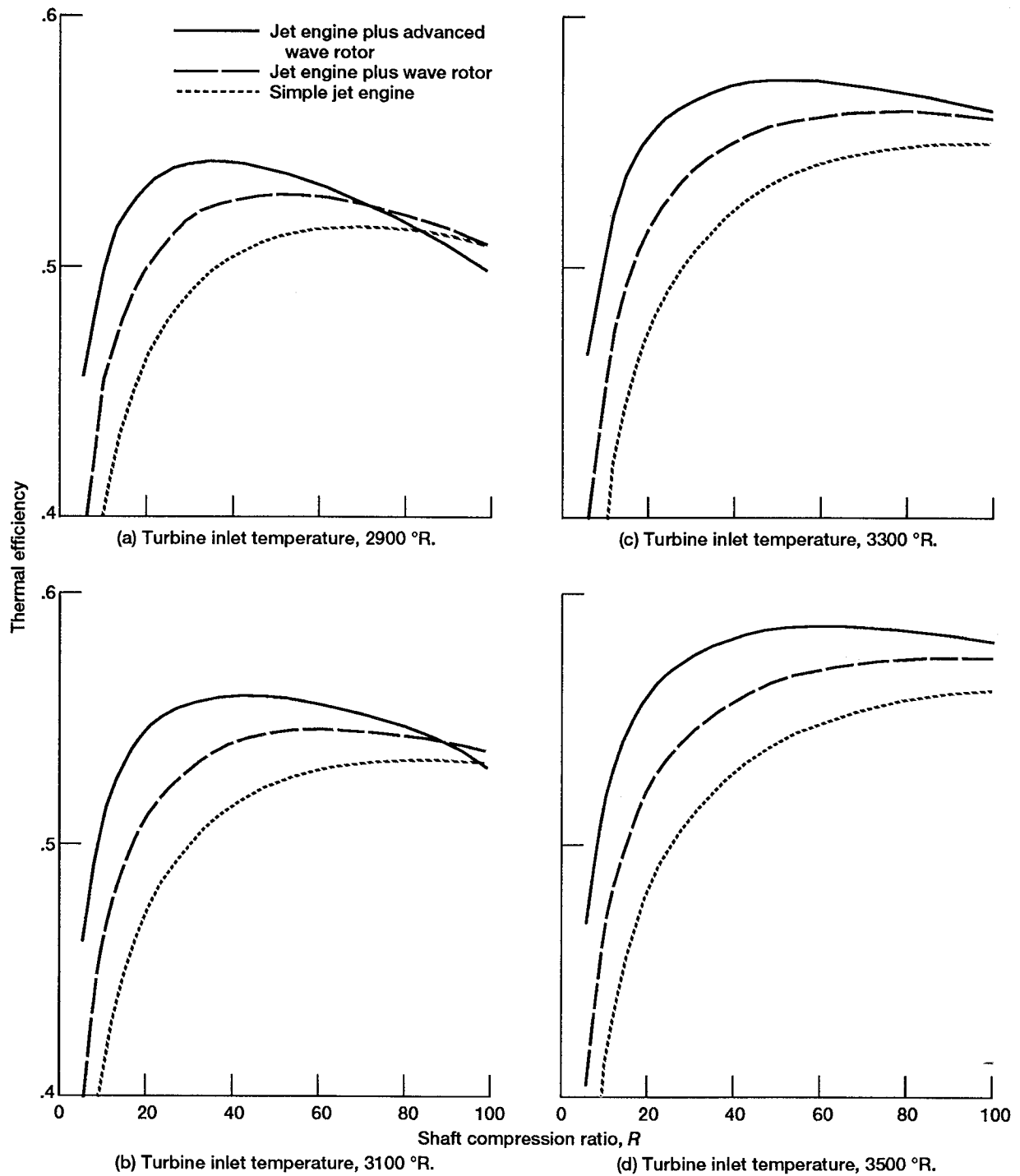


Figure 5.—Thermal efficiency of jet engine with and without wave-rotor topping cycle for engines with same shaft compression ratio.

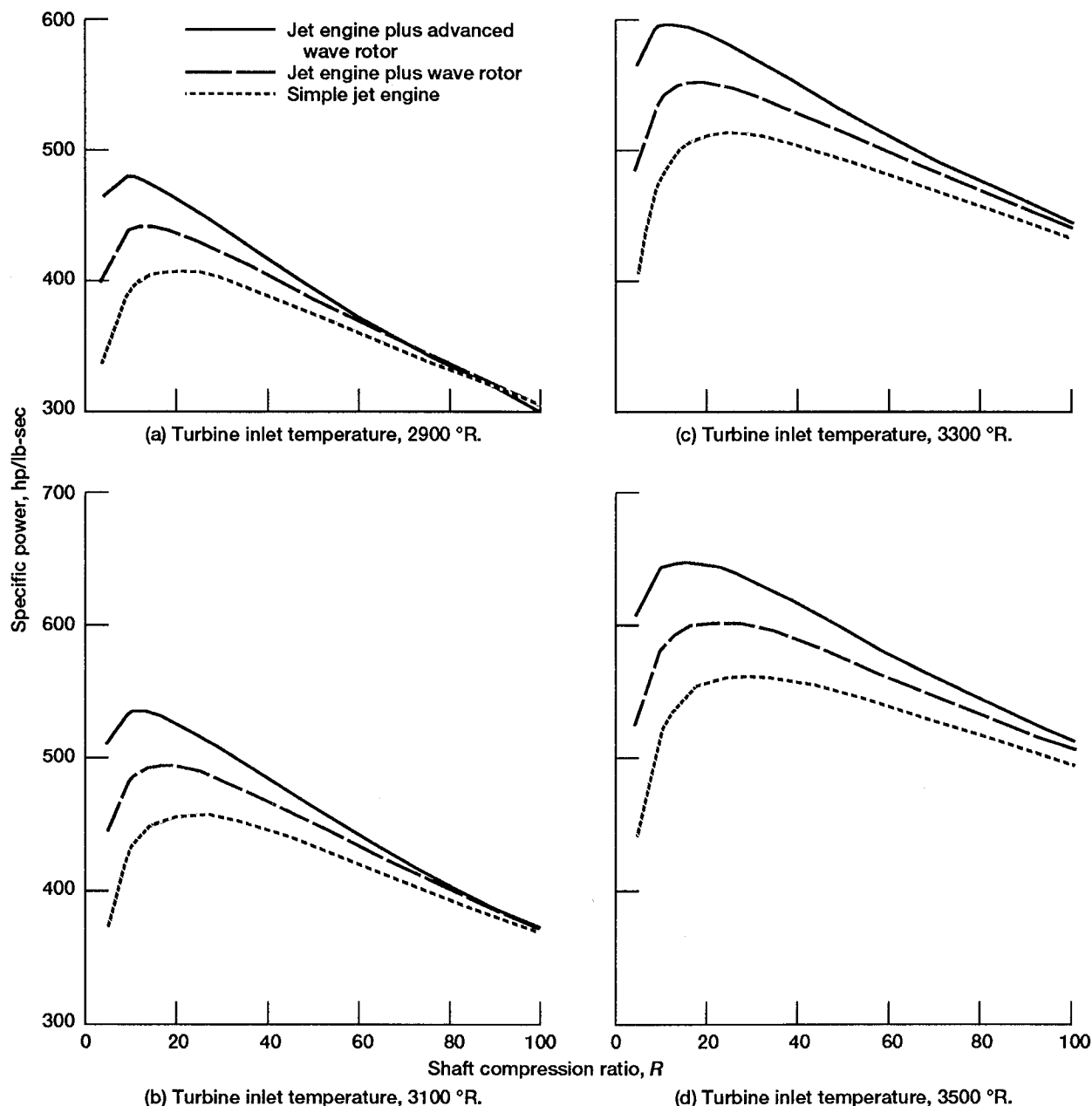


Figure 6.—Specific power of jet engine with and without wave-rotor topping cycle for engines with same shaft compression ratio.

in which the combustion temperature is plotted against shaft compression ratio with turbine inlet temperature as a parameter.

A different view of the advantage of a wave-rotor topping cycle can be seen by considering the design of an engine to meet a specific thermal efficiency goal, say 54 percent. To do this with a simple jet engine would require a compression ratio of 60 at a turbine inlet temperature of 3300 °R. This would require major advances in materials to achieve both the turbine inlet temperature and the high temperatures of the final compressor stages ($T_3 = 1630$ °R). A jet engine plus a wave-rotor topping cycle could achieve the same efficiency at a shaft compression ratio of 40 and a turbine inlet temperature of 3100 °R, a more modest goal

that is within the materials capabilities expected to be available by the turn of the century. If advanced wave-rotor performance could be achieved, the same efficiency goal could be reached at a shaft compression ratio of 35 and a turbine inlet temperature of 2900 °R. This is within the range of current technology and so would require no new material development. Because the wave rotor itself is alternately heated and cooled by the gases flowing through it, it attains a temperature between the turbine inlet temperature and the compressor exit temperature. Its construction is relatively simple and is not likely to require advanced materials. The specific power is approximately identical for the three cases considered here.

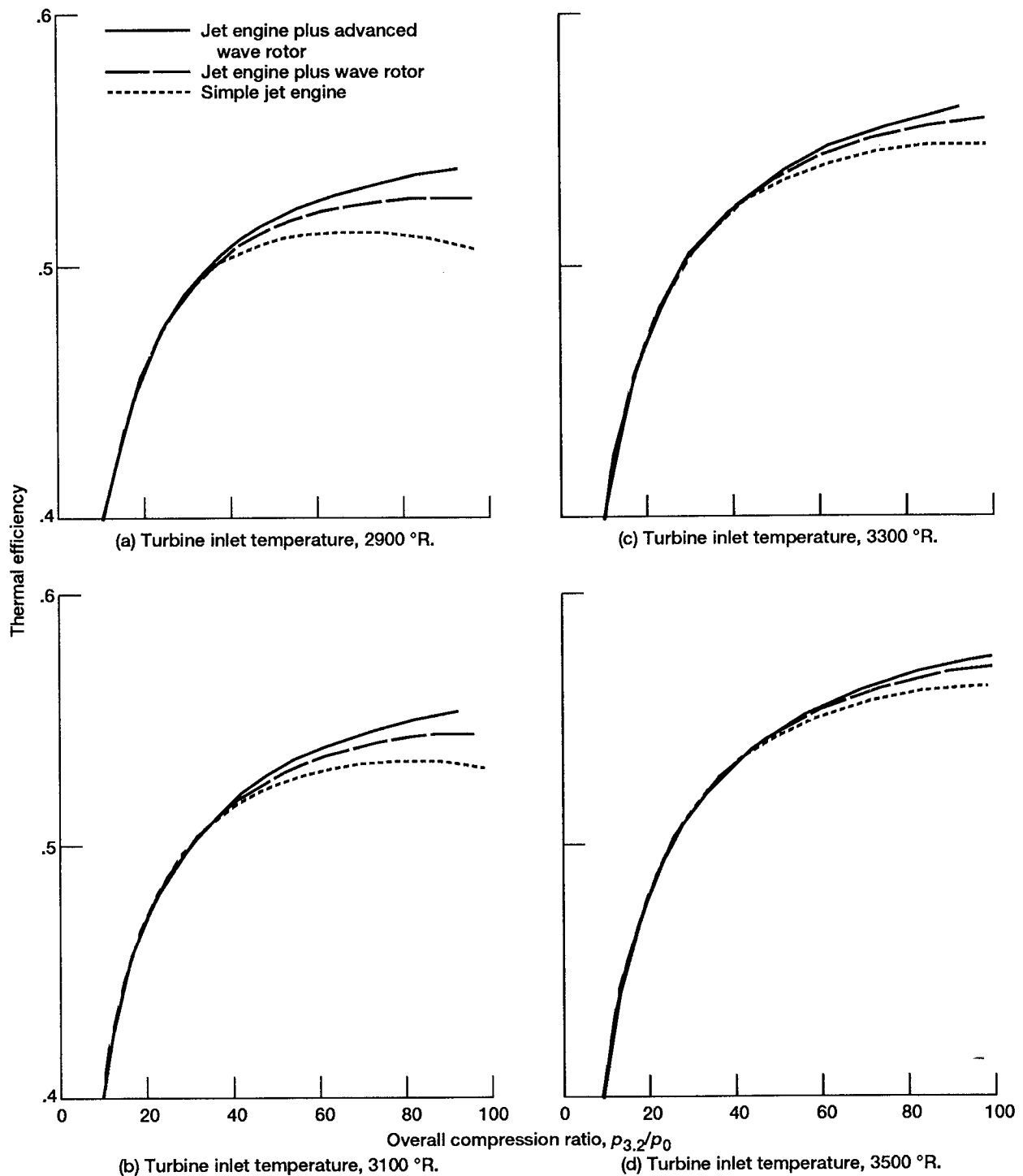


Figure 7.—Thermal efficiency of jet engine with and without wave-rotor topping cycle for engines with same overall compression ratio.

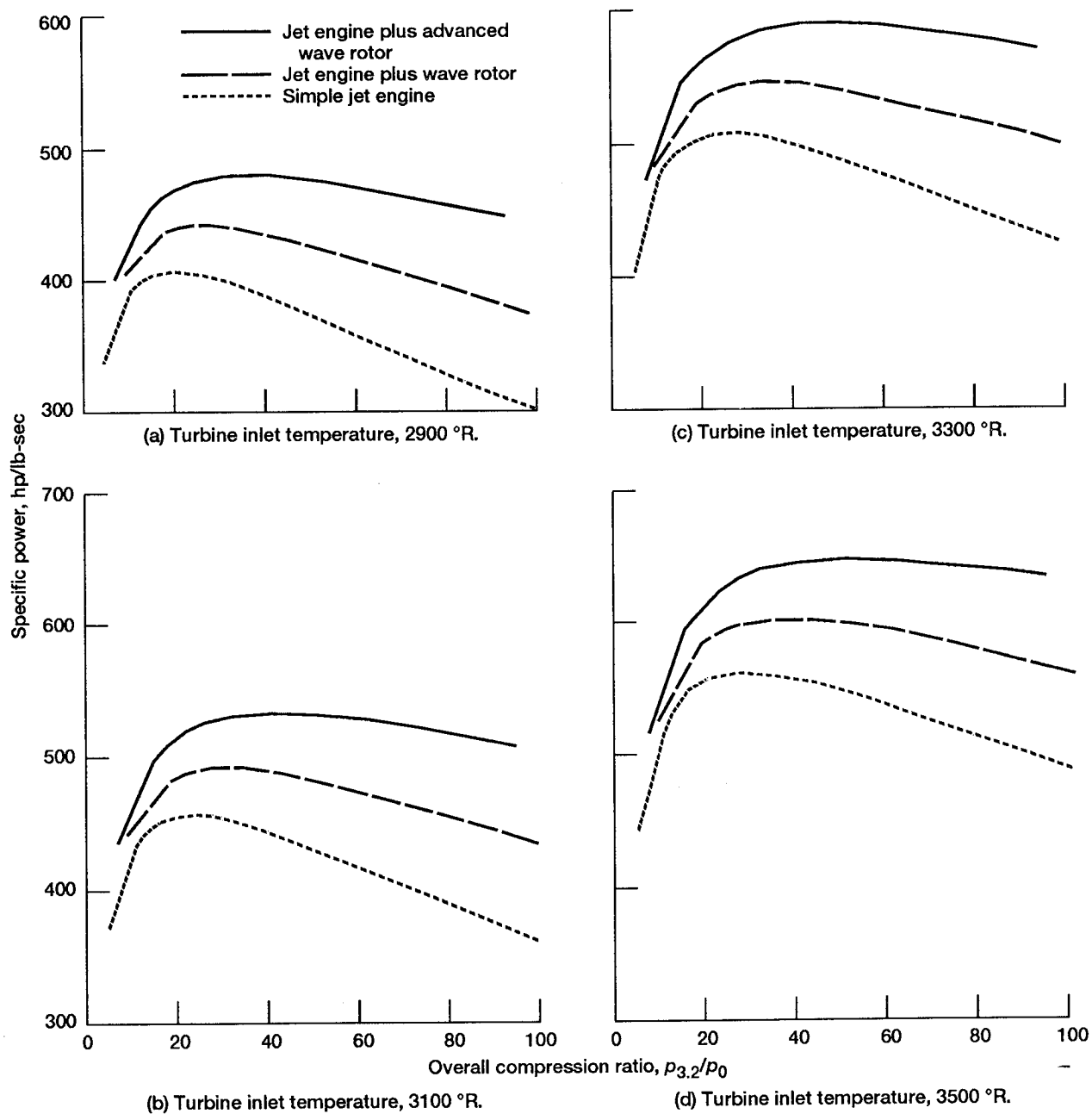


Figure 8.—Specific power of jet engine with and without wave-rotor topping cycle for engines with same overall compression ratio.

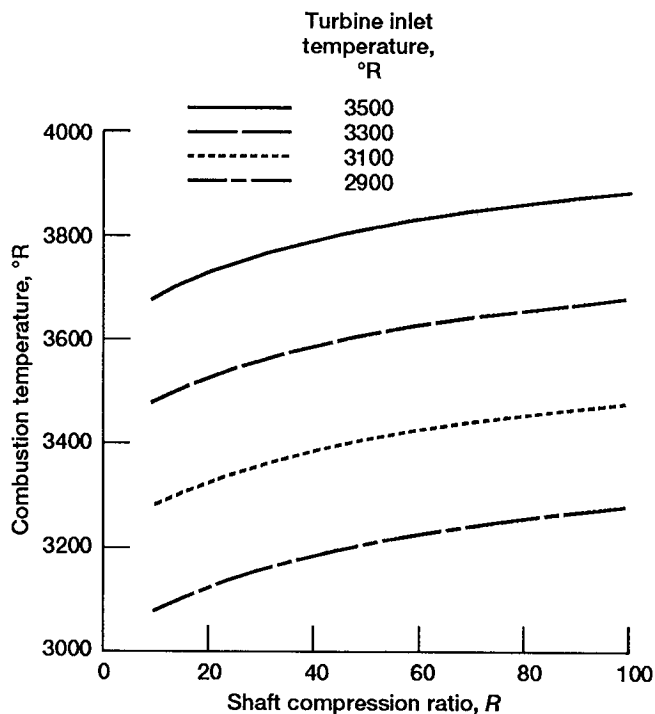


Figure 9.—Combustion temperature as function of shaft compression ratio for jet engine plus wave rotor having characteristic of equation (15) ($PR = 1.8$).

As is well known, increasing the pressure ratio of an engine requires an appropriate increase in turbine inlet temperature if optimum efficiency is to be achieved. This is true whether the higher pressure ratio is obtained by mechanical compressors or wave rotors. For example, if the turbine inlet temperature is 2900 °R, a simple jet engine with a compression ratio of 85 has lower efficiency and lower specific power than a simple jet engine with a compression ratio of 55. Adding a wave rotor to the engine with the compression ratio of 85 only gives the same efficiency as the simple jet with the compression ratio of 55 but with lower specific power and added complexity. Obviously, the simple jet with the compression ratio of 55 is to be preferred to the other two examples. Still, for shaft compression ratios between 22 and 80, the wave-rotor-topped cycle will have higher efficiency than a simple jet engine of any compression ratio, and for overall compression ratios less than 60 the specific power will also be higher.

As the turbine inlet temperature is increased to 3500 °R, the wave-rotor-topped cycle has higher efficiency than any simple jet of lower shaft or overall compression ratio up to, and beyond, the maximum compression ratio calculated here (i.e., 100). Moreover, for overall compression ratios less than 100 (shaft compression ratio of 55), the specific power is greater with the wave-rotor-topped cycle than the maximum achievable with a simple jet (at a compression ratio of 30).

Conclusions

Using a wave-rotor topping cycle on a jet engine will give improved performance over a simple jet engine of the same overall compression ratio. Adding a wave rotor to an existing engine while maintaining the same turbine inlet temperature but increasing the combustion temperature will increase both efficiency and specific power.

This conclusion was based on a comparison of the wave-rotor-topped cycle with a simple jet engine at constant component efficiencies. In fact, as compression ratios get higher, the blades of the high-pressure stages of conventional turbomachinery get smaller, resulting in increased losses and lower component efficiencies. An engine with a wave-rotor-topped cycle may therefore have an even greater advantage over a simple jet engine than is indicated by these calculations.

In addition, wave rotors can deliver improved performance without requiring the development of new materials.

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